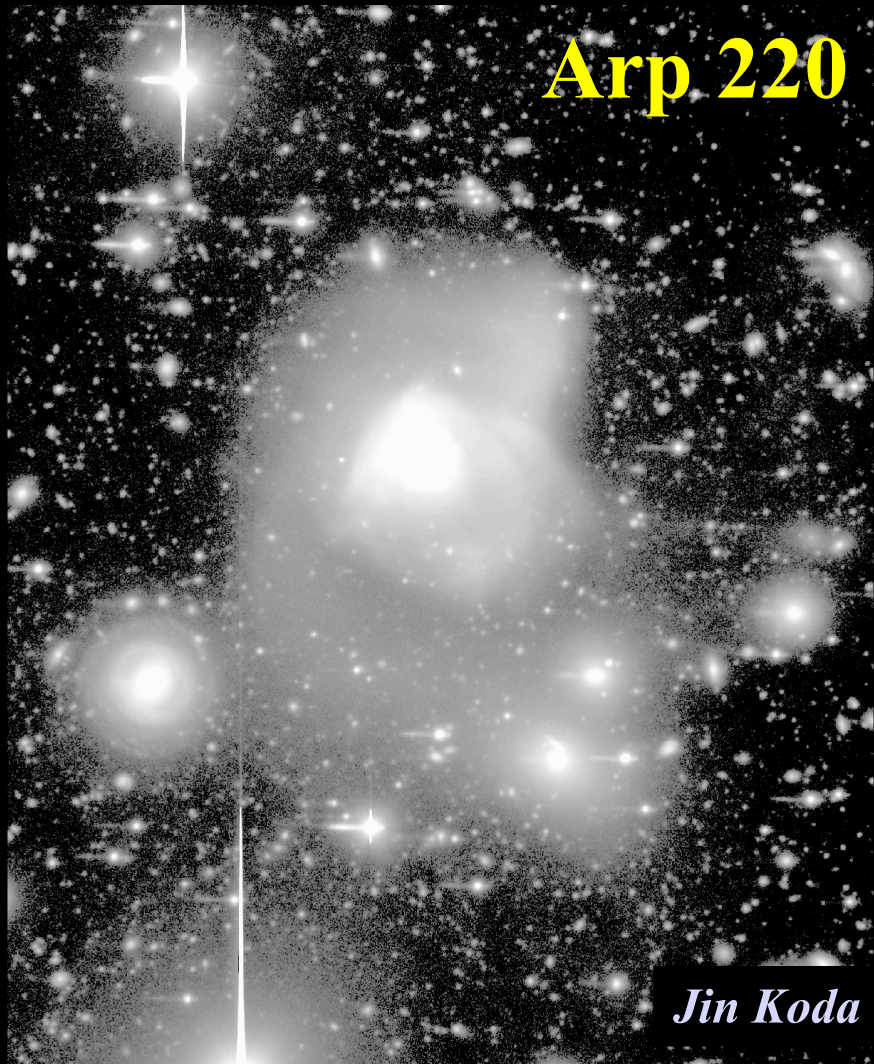
Lecture #2: Ultraluminous Infrared Galaxies

S. Veilleux (U. Maryland)



Plan

- Definitions & Instrumentation
- Properties of ULIRGs: Near & Far
  - Spectral energy distribution
  - Luminosity function
  - Evolution
  - Morphology
  - Gas content
- Importance of ULIRGs
  - Spheroids in formation
  - Black hole growth
  - Galactic winds --- Tomorrow!
- Summary

Relevant Reviews

- **Sanders & Mirabel 1996, ARAA, 34, 749–792**
- **Blain et al. 2002, Physics Reports, 369, 111–176**
- **Lonsdale, Farrah, & Smith 2006, astro–ph/0603031**

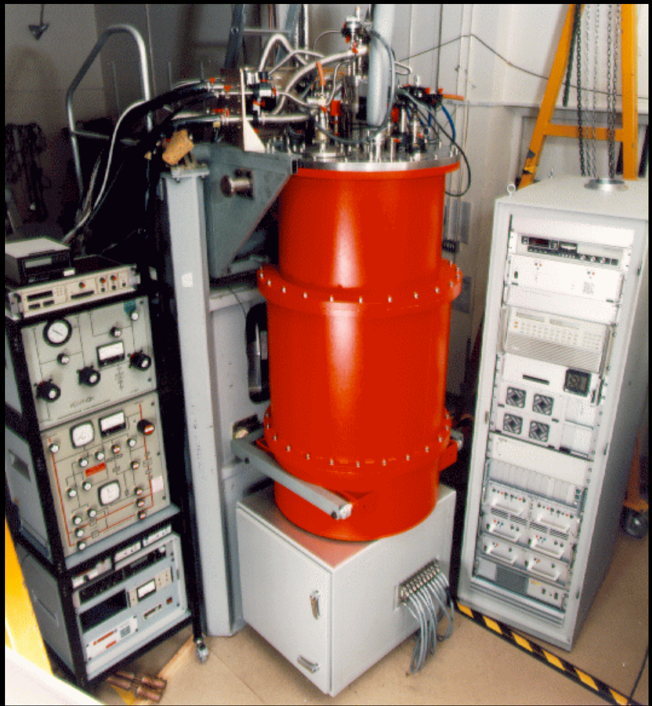
Definitions

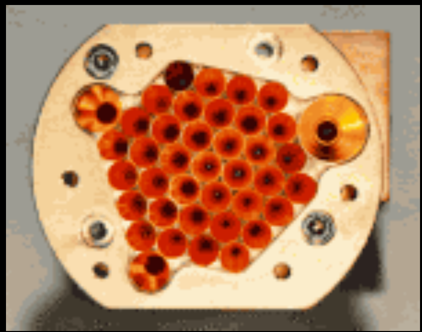
- **Infrared Luminosity**
  $L_{IR} \equiv L(8 - 1000\ \mu m)$
- **Luminous Infrared Galaxies (≡ LIGs or LIRGs):**
  $\log[L_{IR}/L_{Sun}] \geq 11.0$
- **Ultraluminous Infrared Galaxies (≡ ULIGs or ULIRGs):**
  $\log[L_{IR}/L_{Sun}] \geq 12.0$

The James Clerk Maxwell Telescope &

Submillimeter Common User Bolometer Array (SCUBA)

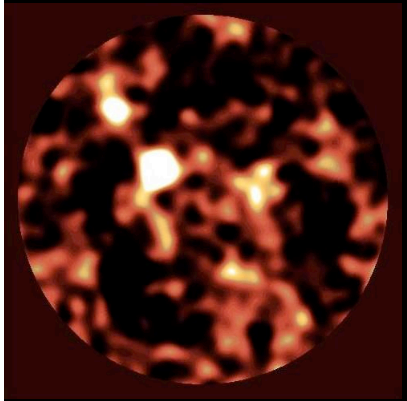
JCMT 14m

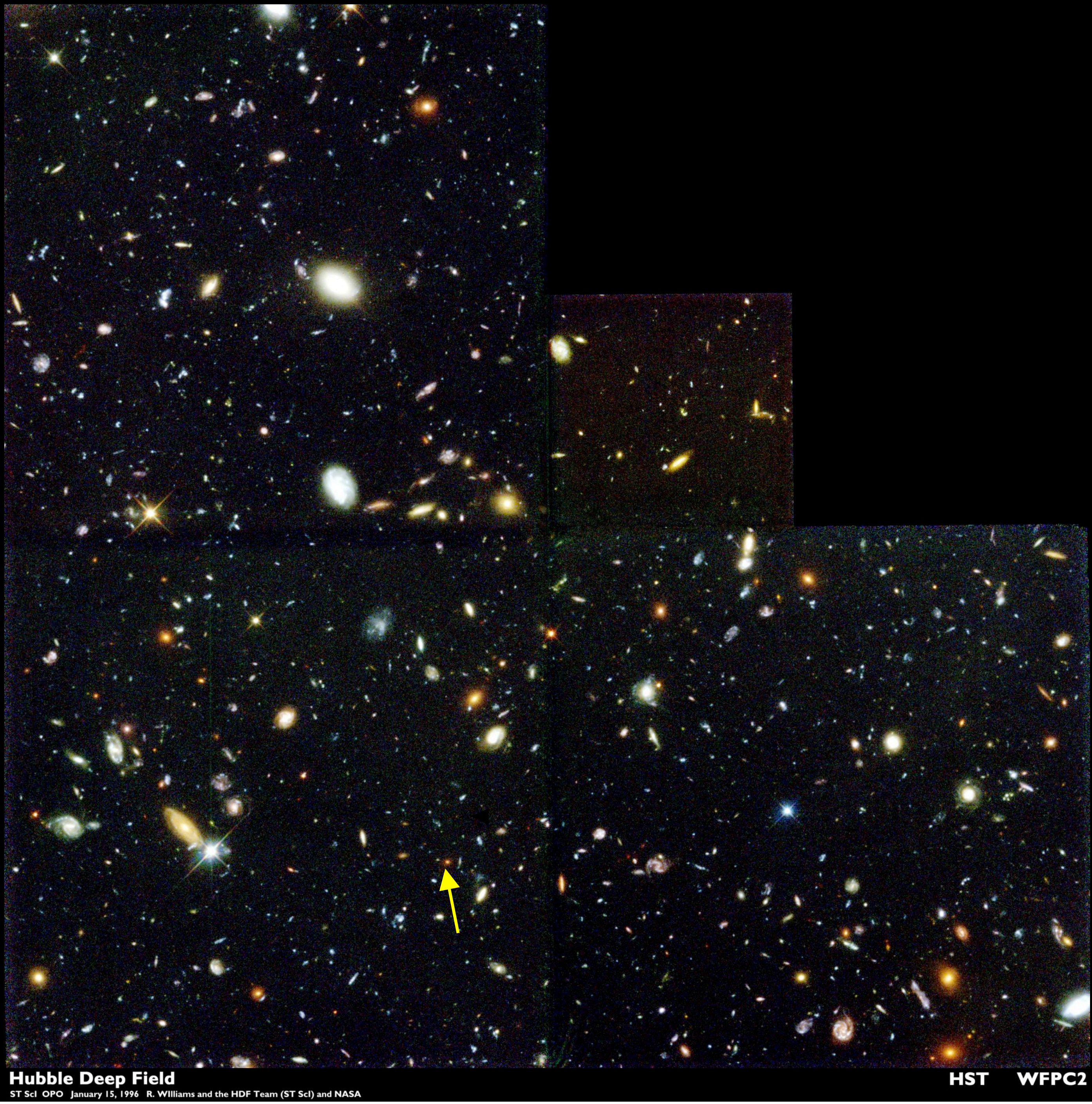




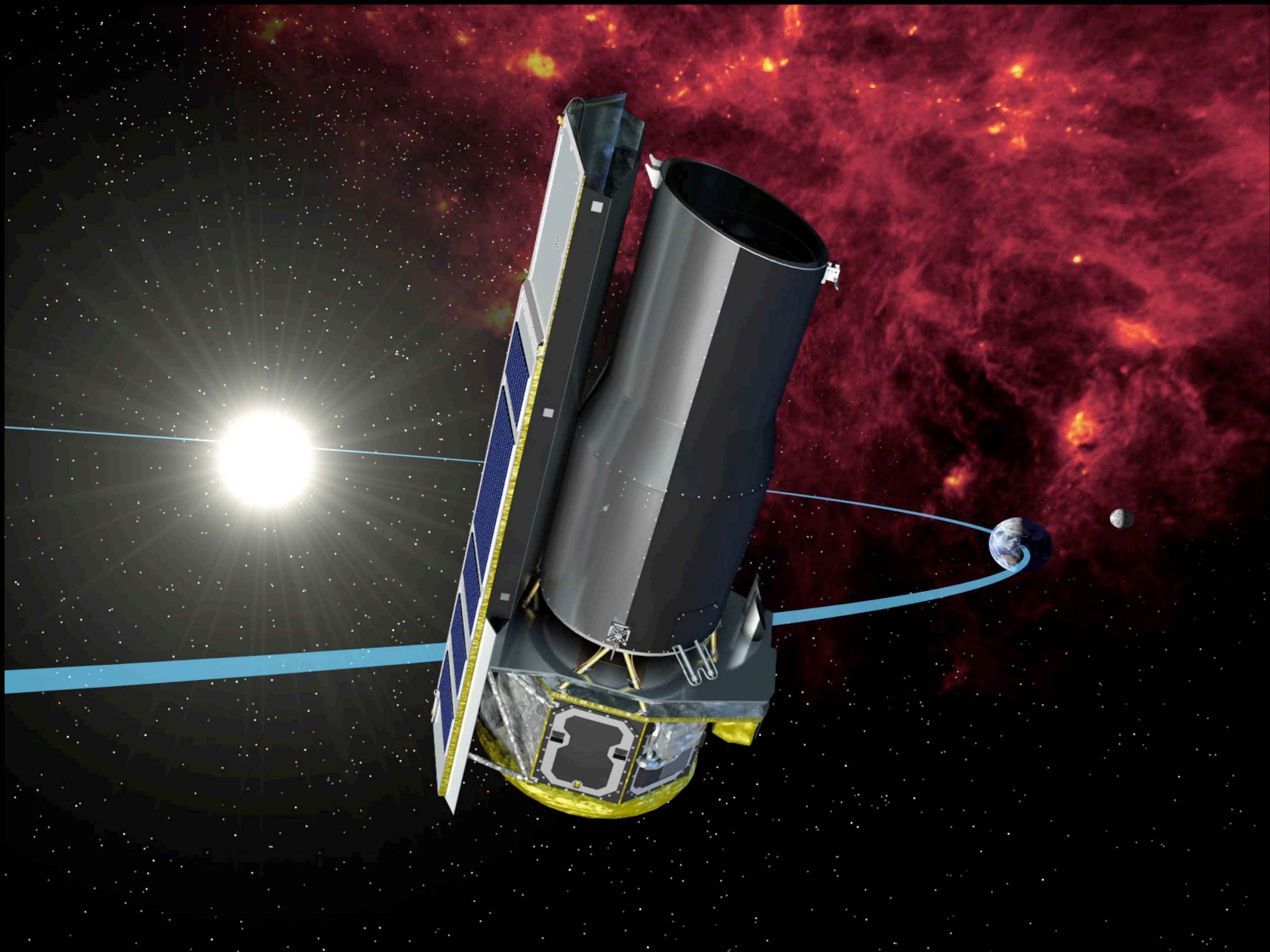
850micron Array

Submm Galaxies (SMGs) in the Hubble Deep Field

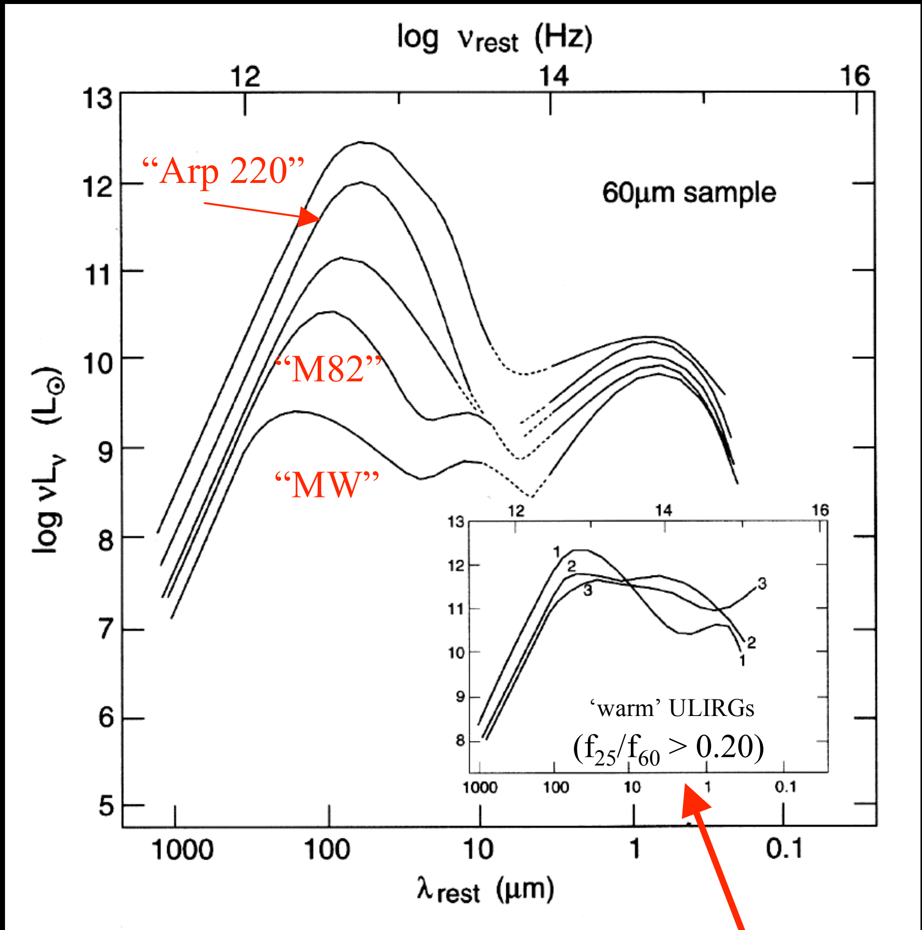




Spitzer Space Telescope

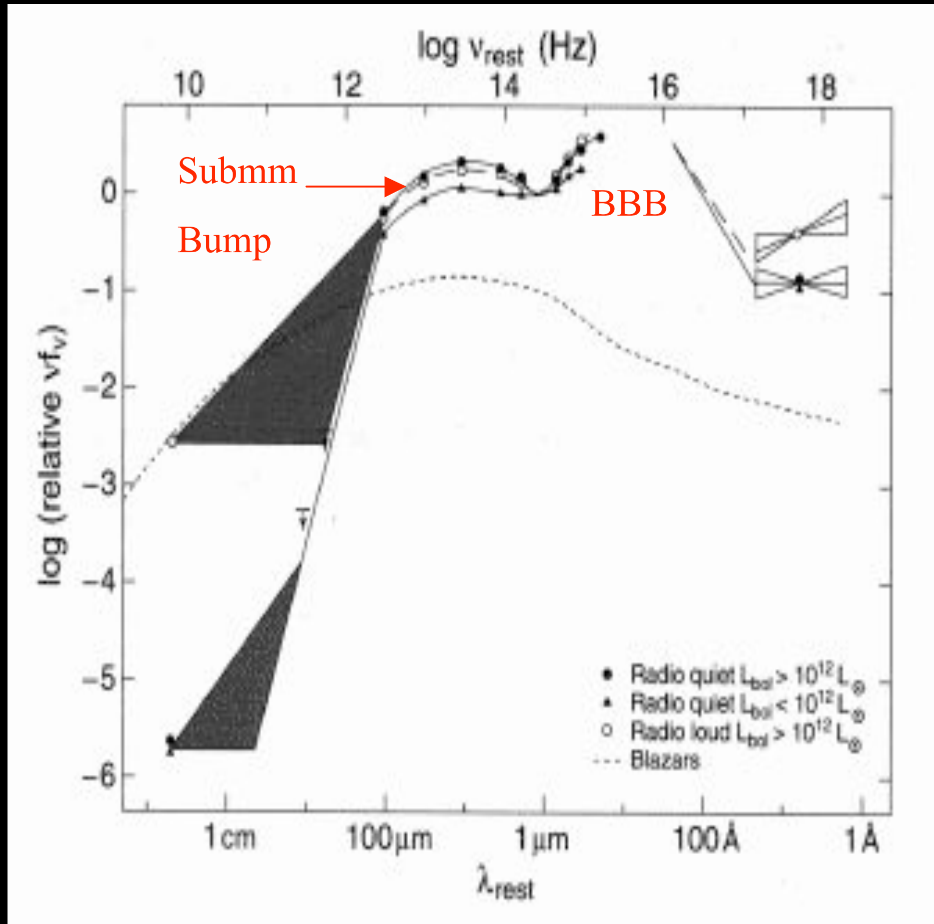


Spectral Energy Distribution



ULIRGs

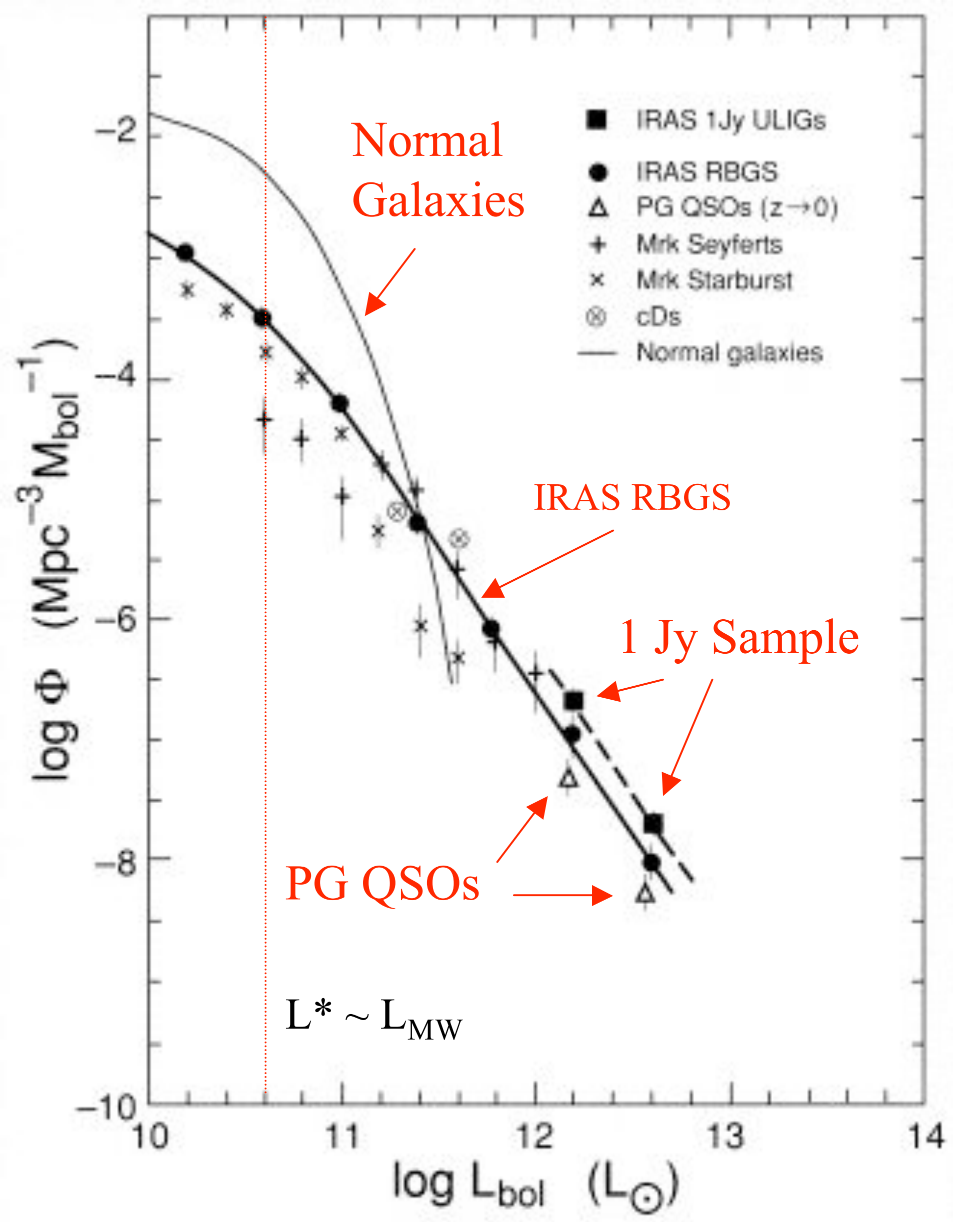
(~ 15% of all ULIRGs)



PG Quasars

(~ 20 – 30% show an IR excess: $L_{IR}/L_{BBB} > 0.4$)

Local Luminosity Function



L_{FIR} high luminosity tail:

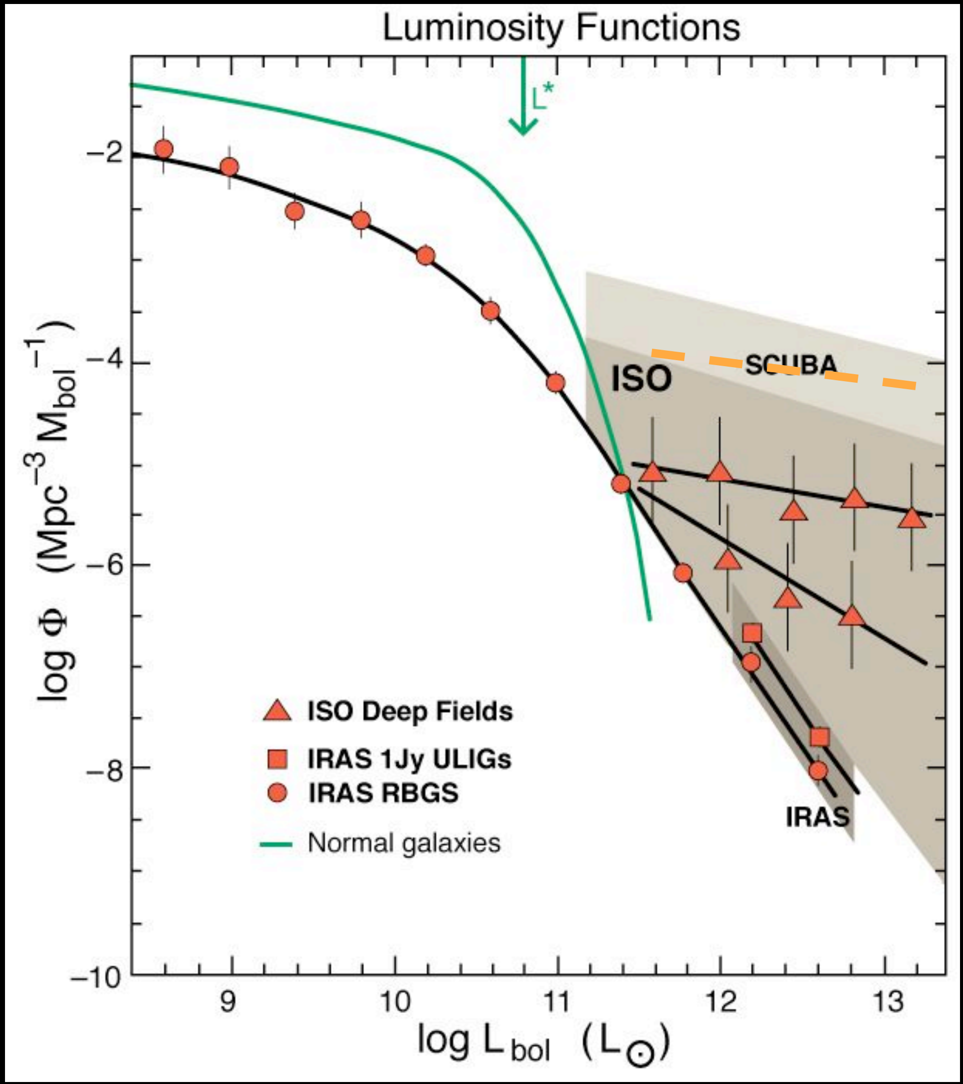
$\Phi \propto L^{-2.35}$

σ (z <0.2) ~ 0.008 deg^{-2}

(Kim & Sanders 1998)

Evolution with Redshift (Pre-*SST*)

n(local ULIRGs) ~ 2.5 x 10^{-7} Mpc^{-3} ~ ***n***(local QSOs)
n(SMGs) ~ $10^{2\text{-}3}$ ***n***(local ULIRGs) ~ ***n***(bright QSOs @ z ~ 2)



Z ~ 2.4 *(Chapman+05)*

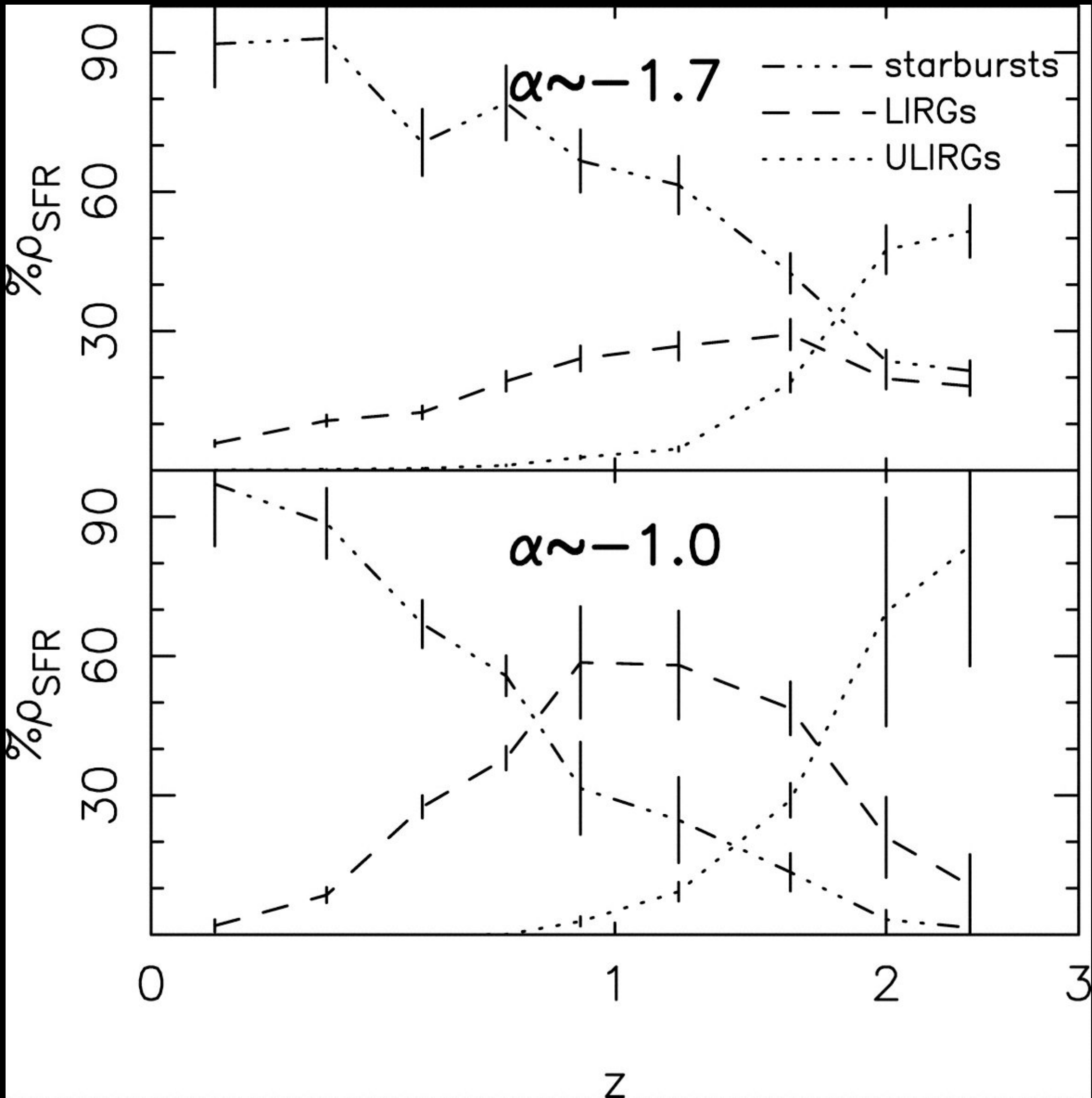
Z=0.80

Z=0.40

Z=0.13 *(Kim & Sanders 98)*
Z=0.045 *(RBGS; Sanders+03)*

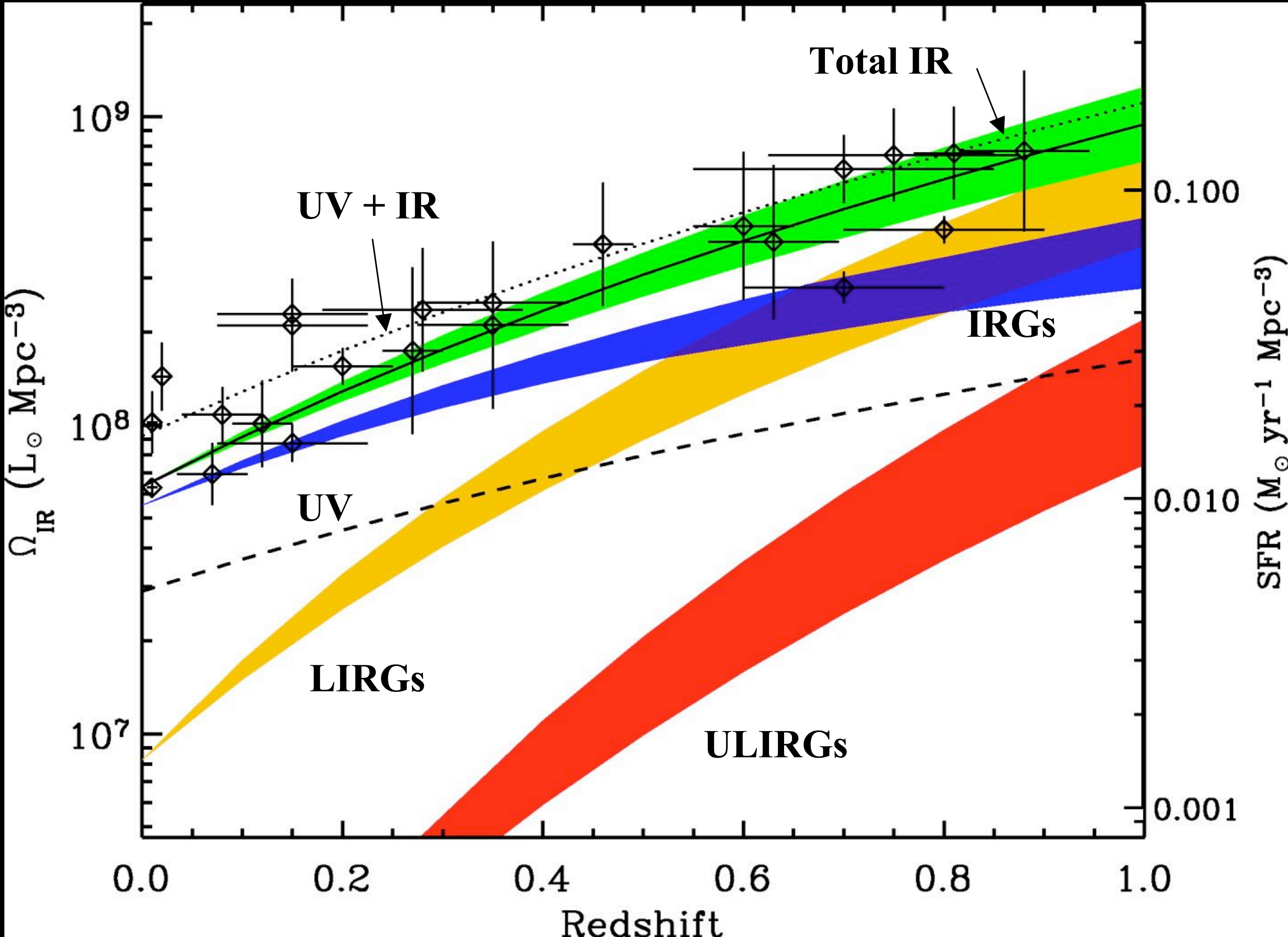
Luminosity Dependence of Evolution

(Post-SST: Perez-Gonzalez et al. 2005)



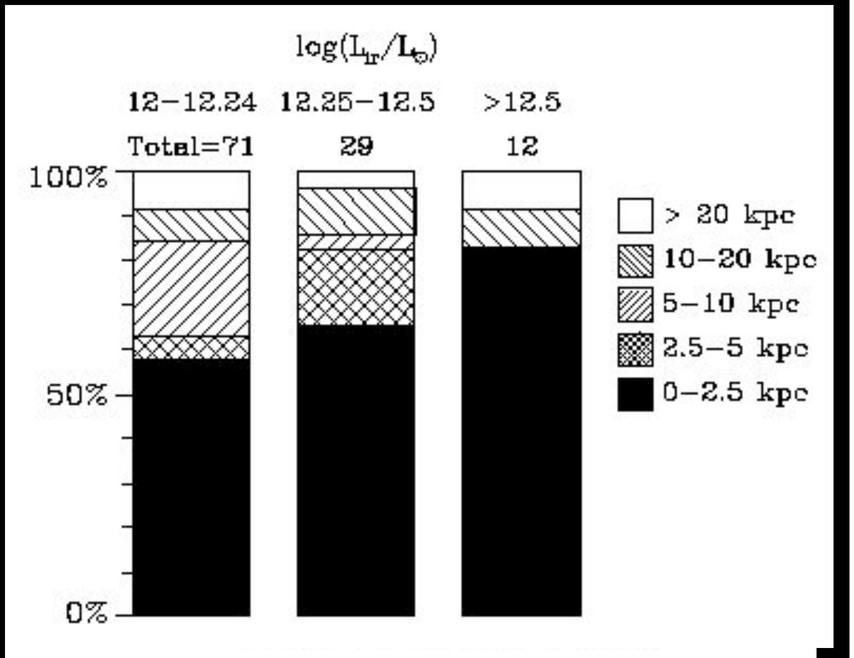
Infrared Background

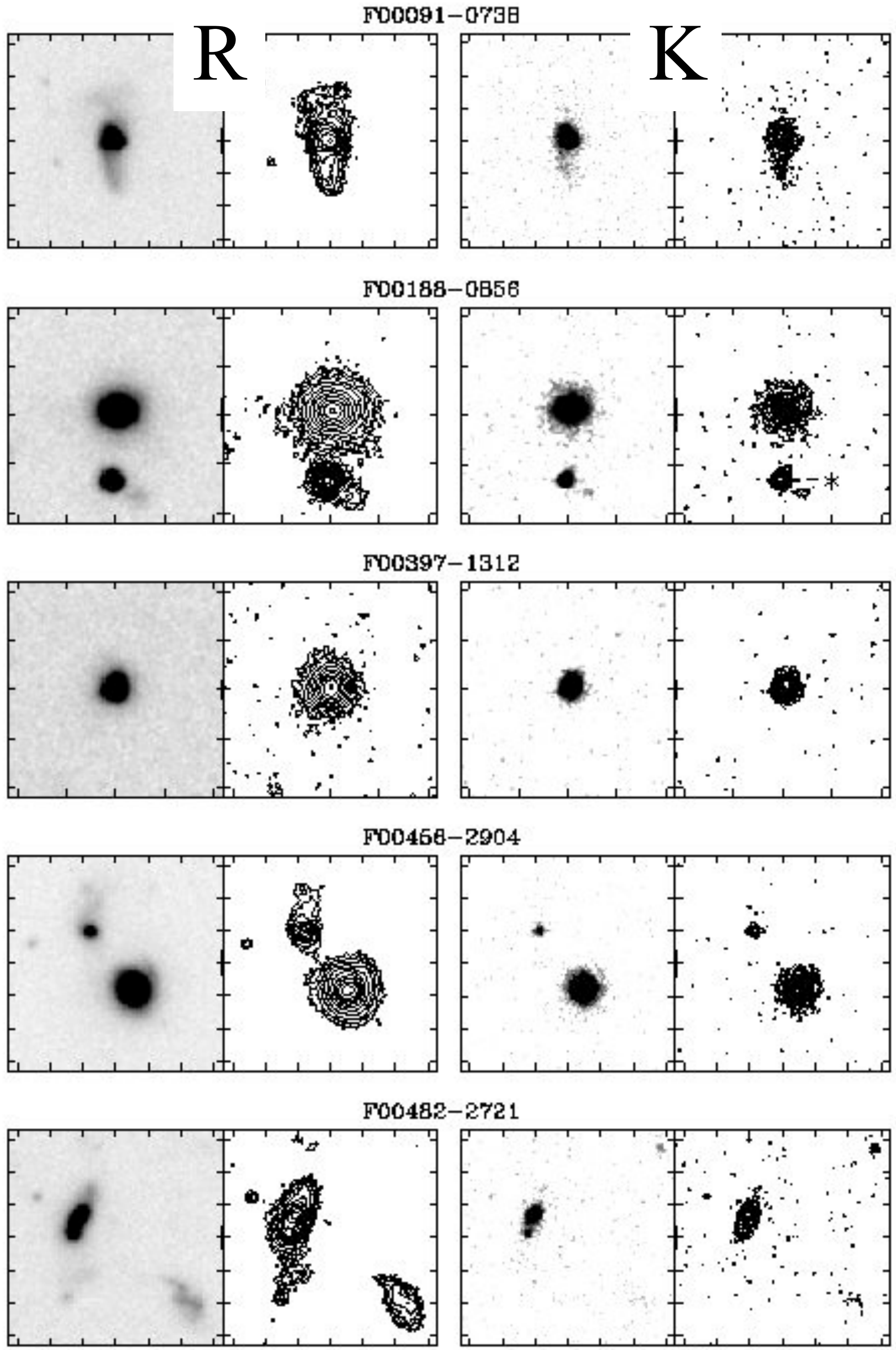
(24-μm selected sample: Le Floc'h et al. 2005)



Morphology of Local ULIRGs *(SV et al. 2002)*

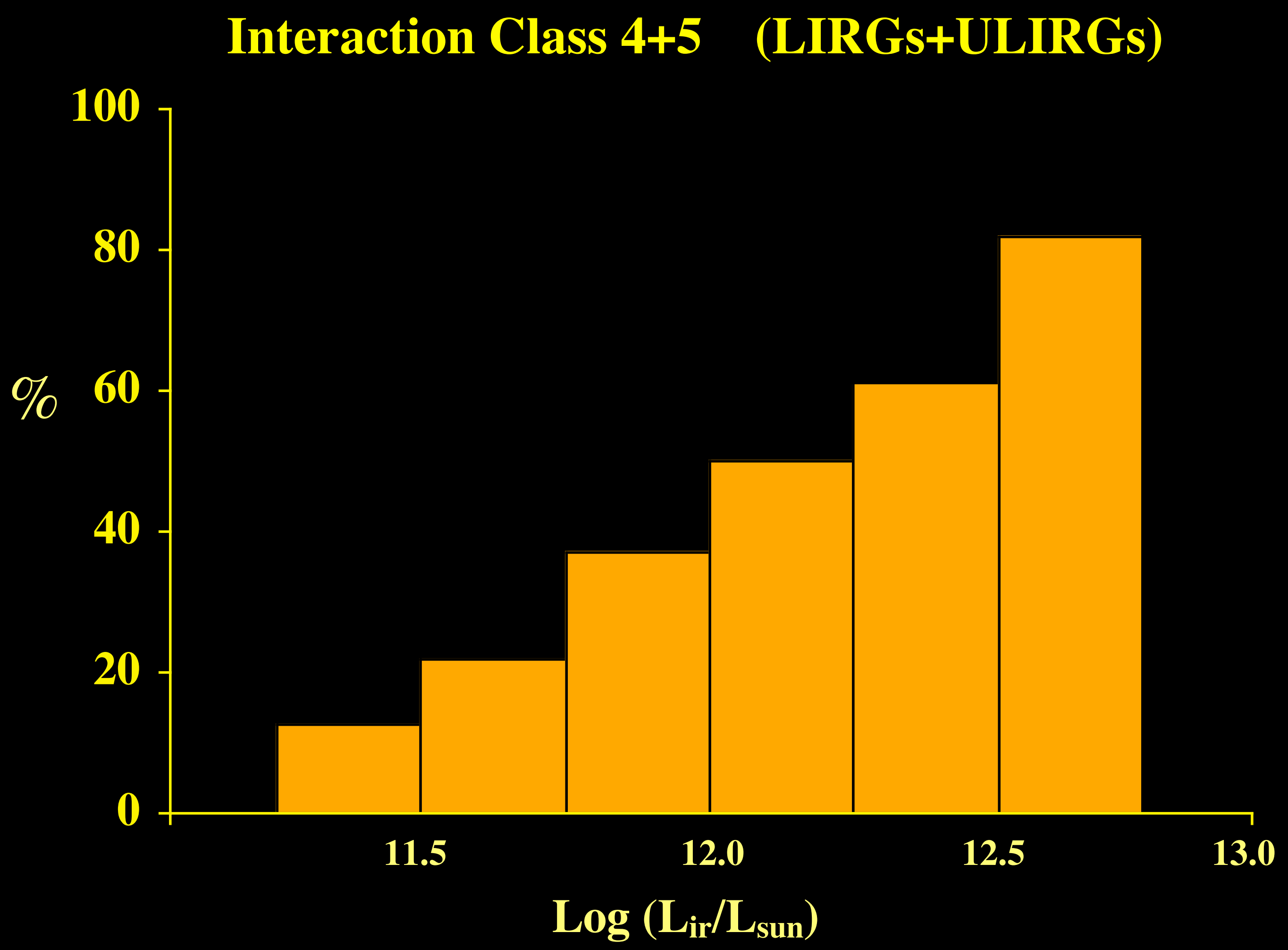
- 56% coalesced to single nucleus
- Fraction of post / old mergers (single nucleus) increases with L_{IR}





Morphology of Local LIRGs + ULIRGs

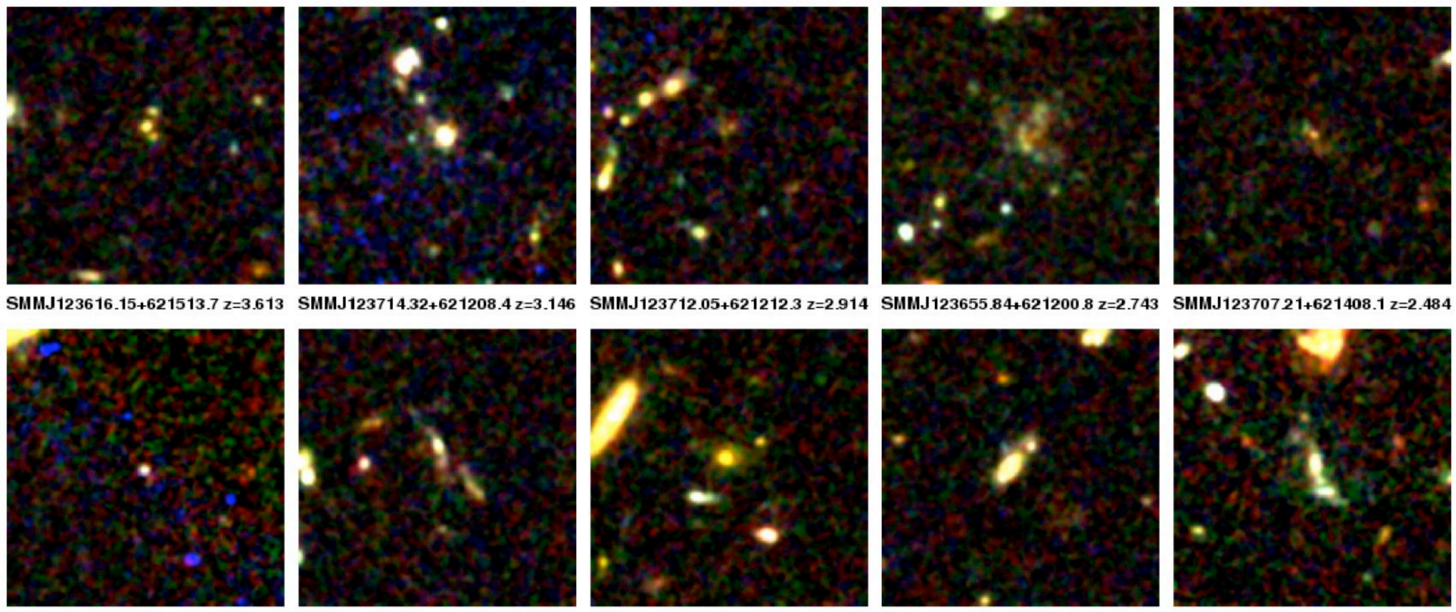
Class
0 no interaction
1 pre-contact
2 first contact
3 merger
4 post merger
5 old merger



(Ishida 2004;
SV et al. 2002)

Distant (z ~ 2–3) ULIRGs: SST & SMGs

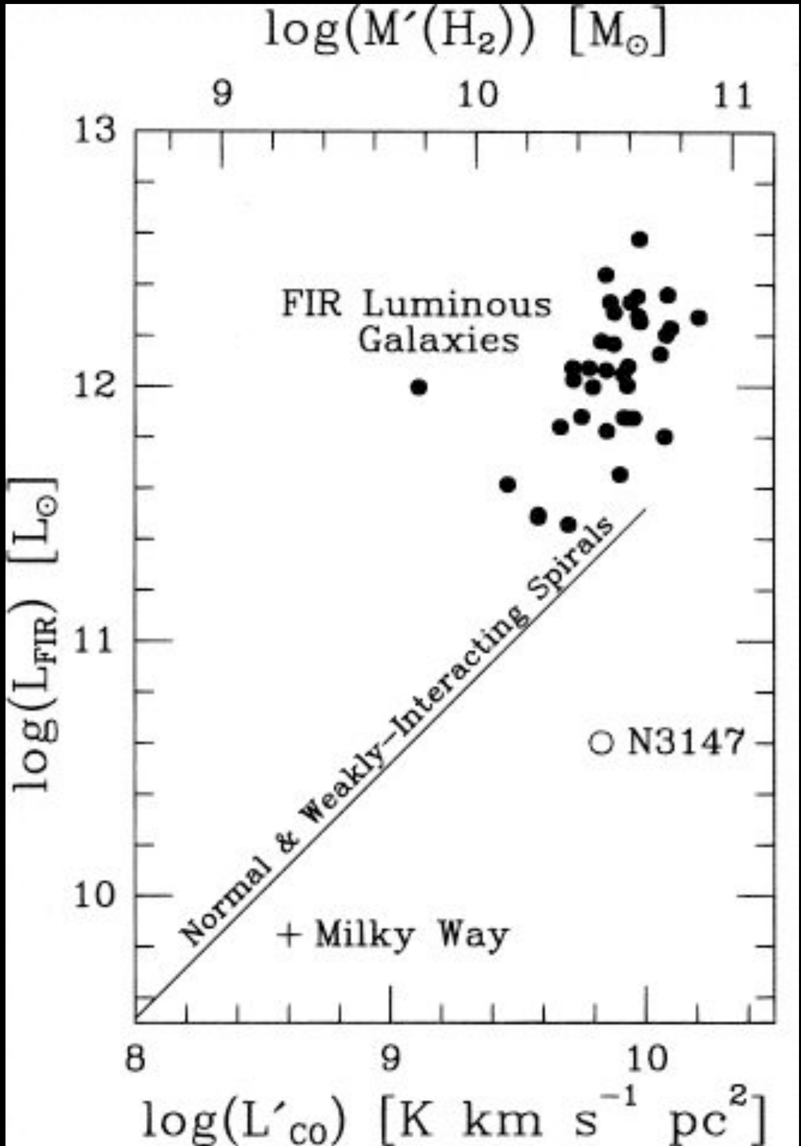
Morphology



Rest–frame BVI

- **Most high-z SMGs (50-60% optical; 85% UV) are multi-component or disturbed systems, suggestive of mergers or interactions** ***(e.g., Chapman+03; Smail+04)***

Gas Content of ULIRGs

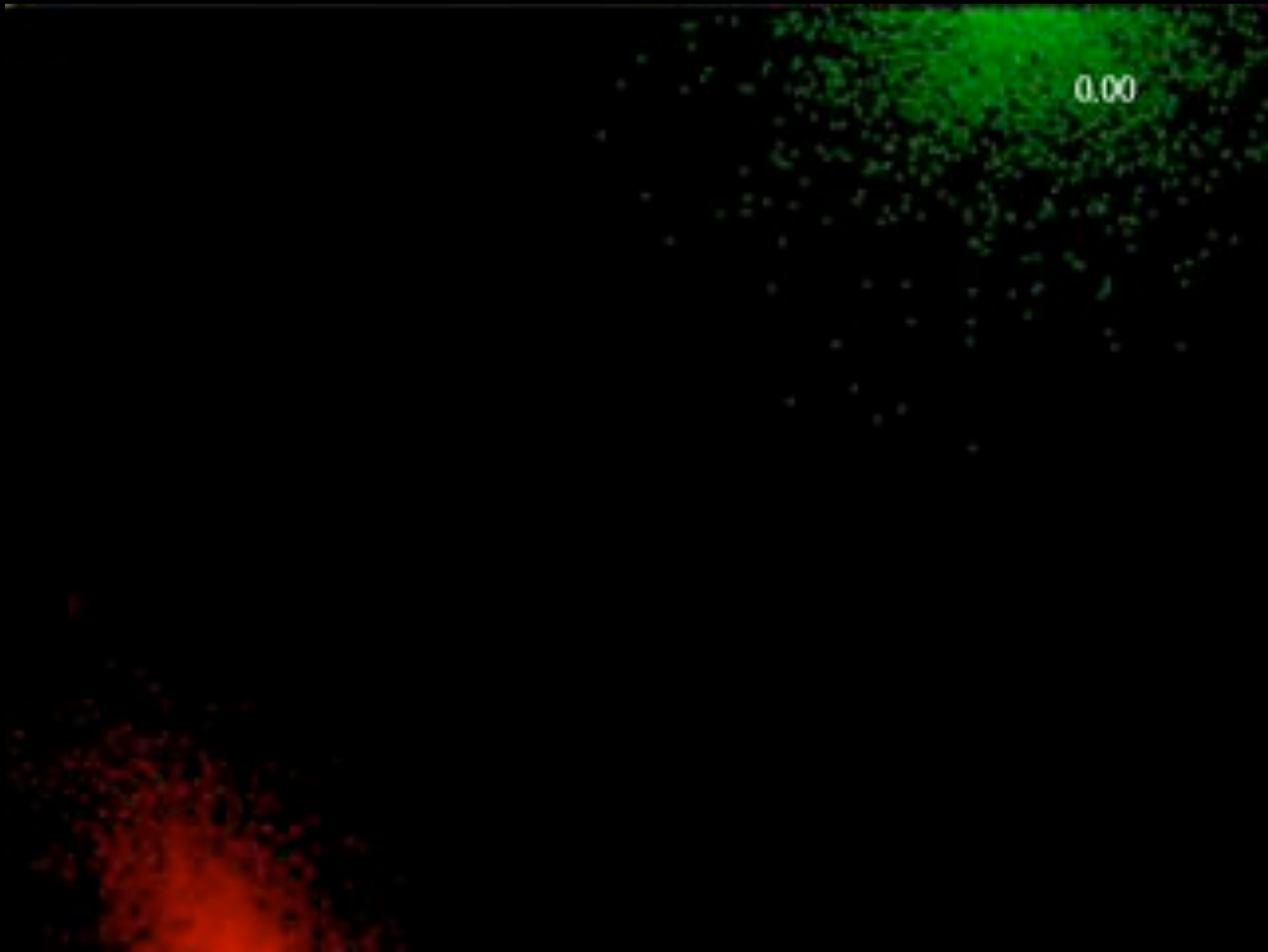


(Solomon et al. 1997)

- $M(H_2)$ = few x 10^{10} M_{Sun}
- $M(H_2)/M(dust) = 10^2 - 10^3$
- Conditions similar to massive GMC cores in our Galaxy but more infrared luminous and denser
- About 40 – 100% of L_{CO} comes from central kpc (also true for L_{MIR})
- $<\Sigma(H_2)>_c \approx <\Sigma_*>$(E cores) $\approx$ few x 10^4 M_{Sun} pc^{-2}

Gas in Galaxy Mergers

(Barnes & Hernquist 1996)



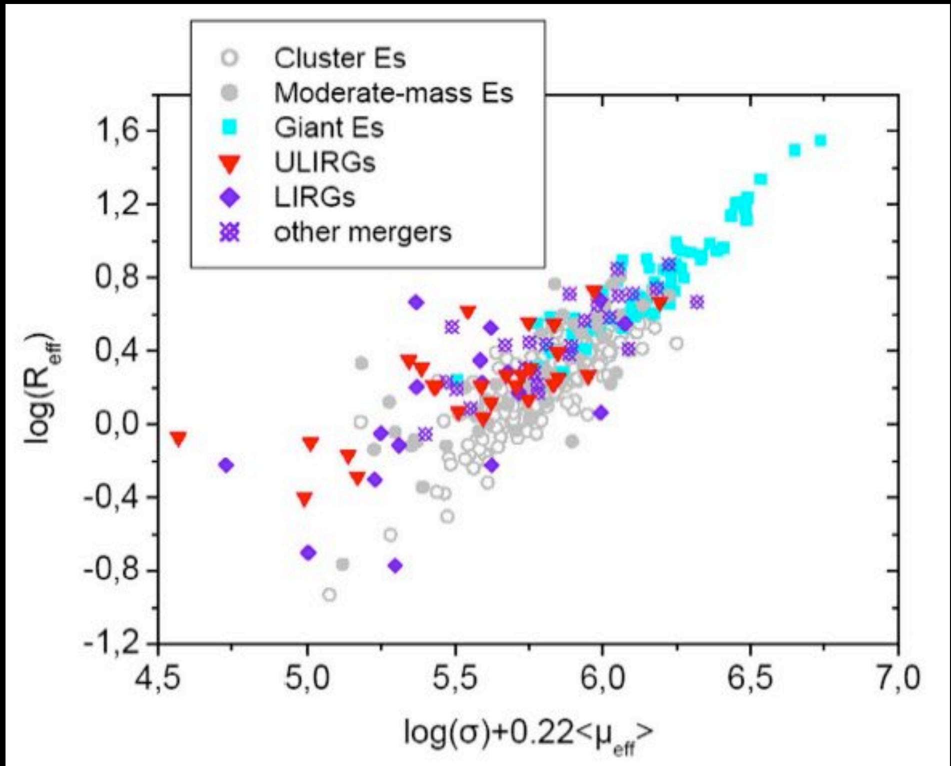
Black Holes during Galaxy Mergers

(Courtesy P. Madau)

Fundamental Plane for Ellipticals and ULIRGs

(SV et al. 2006a, Dasyra et al. 2006ab)

- $\langle M_H \rangle_{host}$ ~ 1 – 2 L* (HST H-band, broad scatter)
- ~ 80% have prominent early-type morphology (r$^{1/4}$-law profile @ r ~ 1.5 – 6.0 kpc)
- $<\sigma> = 161 \pm 40$ km s^{-1}, $<V_{rot} / \sigma> \sim 0.5$ (0.2 – 1.2) among ULIRGs
- ULIRGs are moderate-mass (~ m*) Es with some scatter



Comparison of SMGs and Local ULIRGs

	SMGs	Local ULIRGs	
$\langle v_c \rangle$	400 km/s	250 km/s	
$\langle M_{dyn,1/2} \rangle$	$7\mathrm{x}10^{10}\ M_\odot$	$5\mathrm{x}10^{9}\ M_\odot$	
$\langle R_{1/2} \rangle$	2.0 kpc	0.6 kpc	
$\langle L_{bol} \rangle$	$10^{13.1}\ L_\odot$	$10^{12}\ L_\odot$	
M_{gas}/M_{dyn}	0.3-0.4	0.16	
Σ_{dyn}	$5000\ M_\odot/pc^2$	$4900\ M_\odot/pc^2$	$\sim \Sigma_{E/S0}$

Formation of Spheroids

- **Local ULIRGs: 1-Jy sample**
  - **Location of single-nucleus systems on the FP is consistent with ~ m* spheroids in formation**
  - ***n*(ULIRGs) ~ *2.5 x 10^{-7} Mpc^{-3} ~ (1/7000) n(SDSS ellipticals)***
- **Distant ULIRGs: SST & SCUBA**
  - **$M_{stellar}$ & M_{dyn}(core) consistent with ~ 10^{11} M_{sun} spheroids in formation**
  - **τ(ULIRG lifetime) ~ 200 – 300 Myr ~ τ(gas consumption) ~ 40 Myr**
  - **σ(z, ULIRG era) ~ 1.5 → τ(ULIRG era) ~ 1.5 Gyr**
  - ***n*(descendants) = *n*(bright SMG) x τ(ULIRG era) / τ(ULIRG lifetime)**
    ~ 3 x 10^{-5} Mpc^{-3} (1500 / 300) ~ 1.5 x 10^{-4} Mpc^{-3}
    ~ *n*(> L* ellipticals at z ~ 0)
  - **$\langle M_K \rangle$ = –26.4 *(z = 2.2)* → $\langle M_K \rangle$ ~ –25 *(z = 0)***

Local ULIRGs: SMBH Growth

Fraction of AGN (Seyfert nuclei):

- ~ 1/3 @ $\log[L_{IR}/L_{Sun}] > 12$
- ~ 1/2 @ $\log[L_{IR}/L_{Sun}] > 12.3$

- **Optical & NIR spectroscopy:** ***Ground-based telescope facilities***
- **MIR spectroscopy:** ***Infrared Space Observatory, Spitzer Space Telescope***
- **Radio:** ***VLA, VLBA***
- **X-rays:** ***Chandra X-ray Observatory, XMM-Newton***

Trends with Merger Phases

(Local ULIRGs: SV, et al. 2002, 2006)

- **Nearly all quasar-like ULIRGs are advanced mergers**
- **Starburst-like ULIRGs are found in all merger phases**
- **Warm, AGN-like ULIRGs live in early-type hosts**
- **Tidal features are weaker among warm, AGN-like, early-type ULIRGs**

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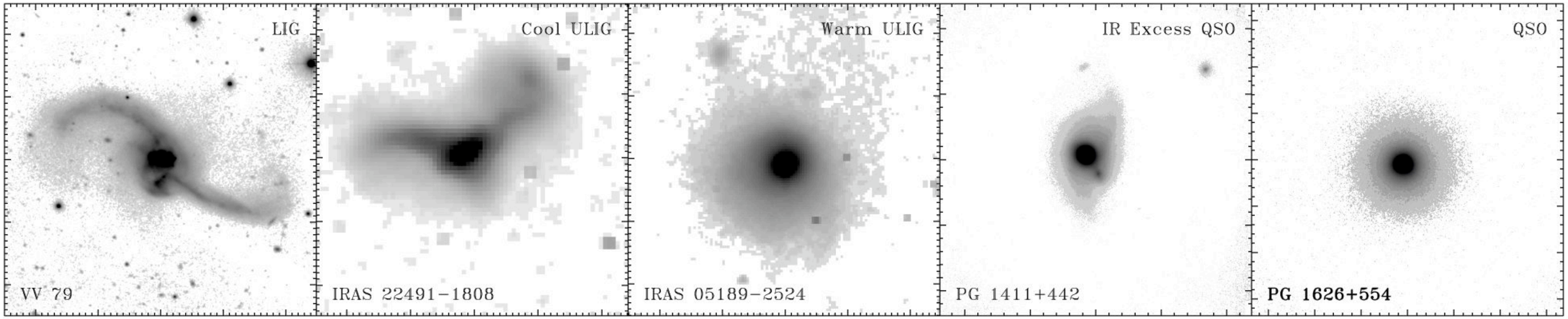
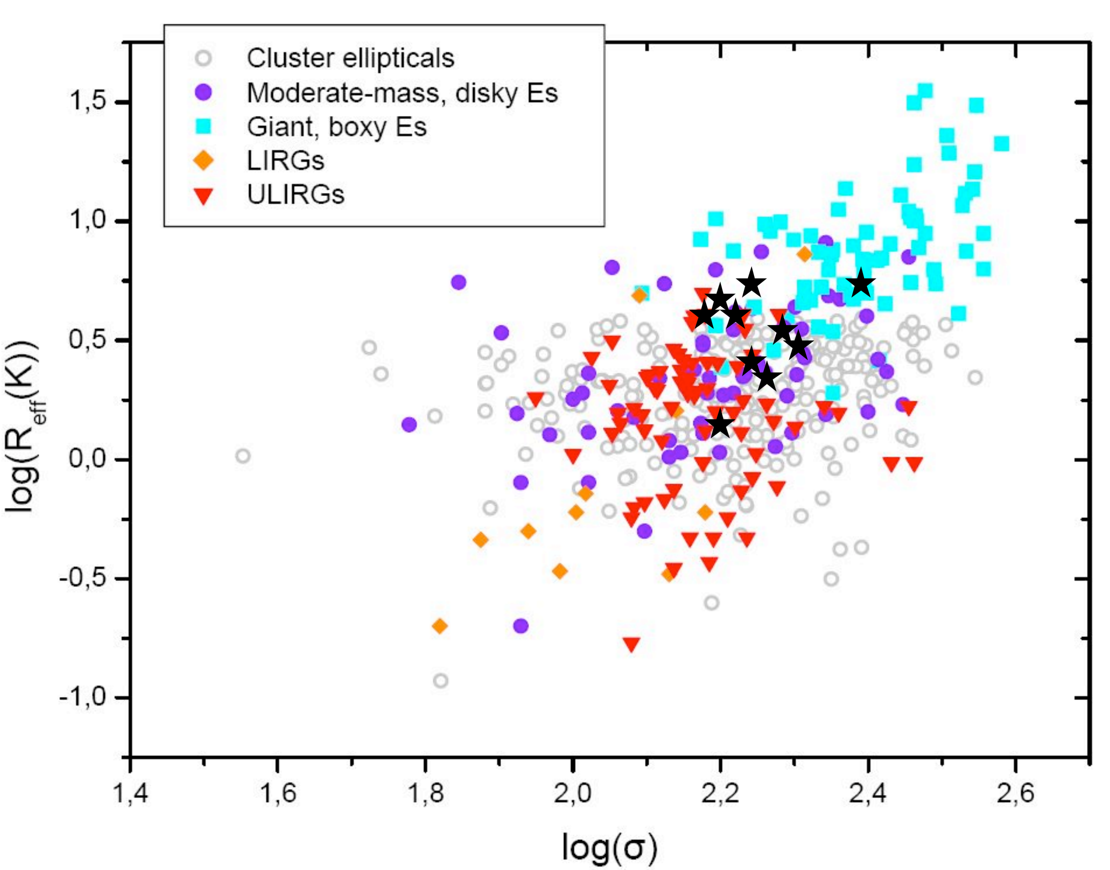


LIRG (S+S) → ULIRG → QSO (E)

Velocity Dispersion Distributions of QSOs

(Dasyra et al. 2006ab, 2007)



<u>Mean velocity dispersions</u>

Giant
Ellipticals: 271± 11 km/s
Moderate mass
ellipticals/S0: 150 ± 12 km/s
Sa/Sb bulges: 120 ± 10 km/s
ULIRGs: 161 ± 40 km/s
PG QSOs: 185 ± 24 km/s

→ similar to ULIRGs

Properties of ULIRGs and QSOs

Dasyra et al. 2007

	log L_{bol} ….	m/m* $m^* = 1.4 \times 10^{11}\ M_\odot$	log m_{BH} ($M_\odot$)	η_{Edd}
<ULIRGs>	12.2	0.8	7.9	0.5
PG QSOs	12.2	1.5	8.0	0.3
		$\sim r_{eff}\sigma^2$	$\sim \sigma^4$	

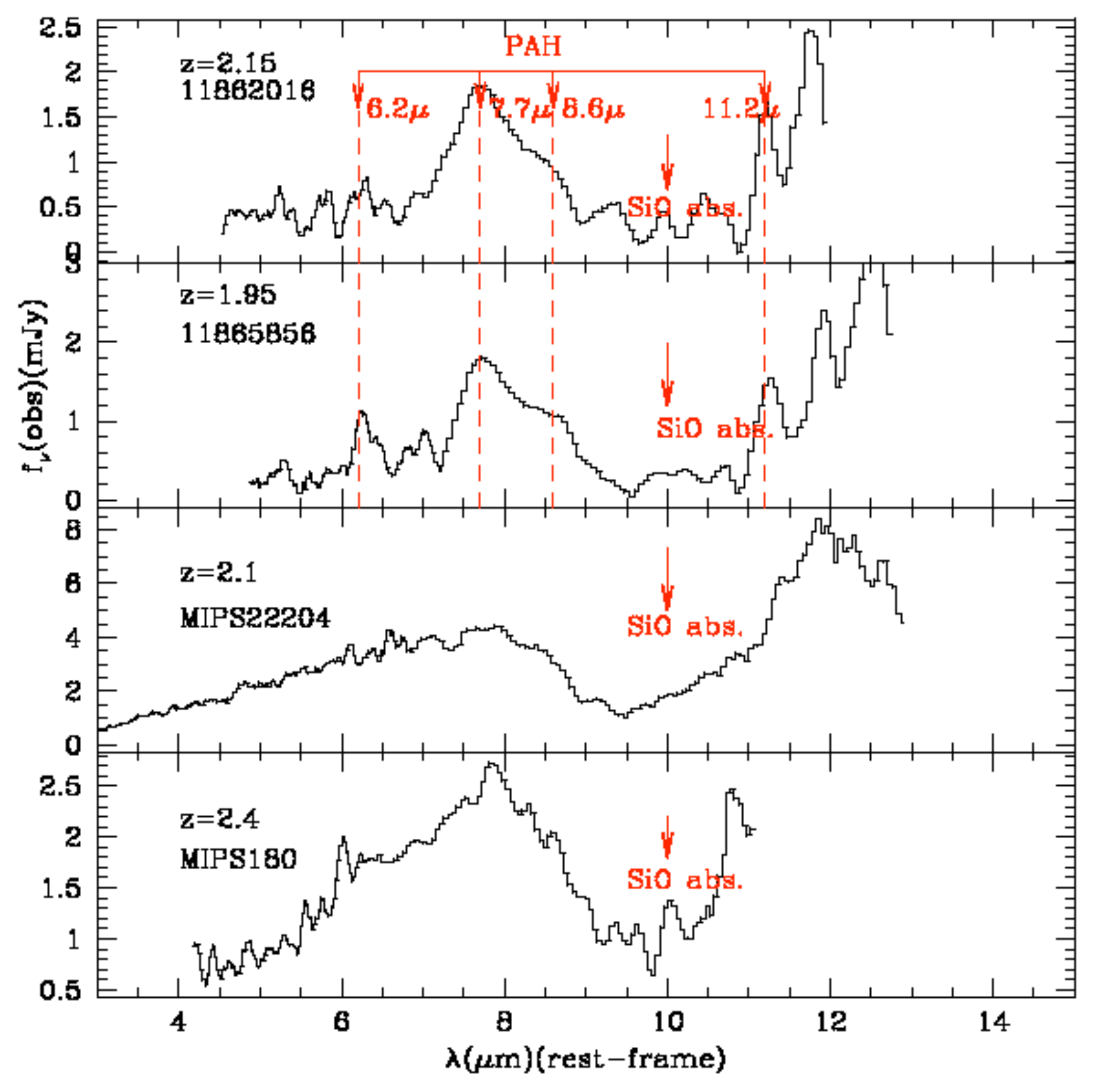
Distant ULIRGs: SMBH Growth

Fraction of AGN (Seyfert nuclei):

- ~ 50 - 75% @ $\log[L_{IR}/L_{Sun}] > 12.5$
- But apparently AGN is not dominant

(SMGs)

Distant ULIRGs: SMBH Growth

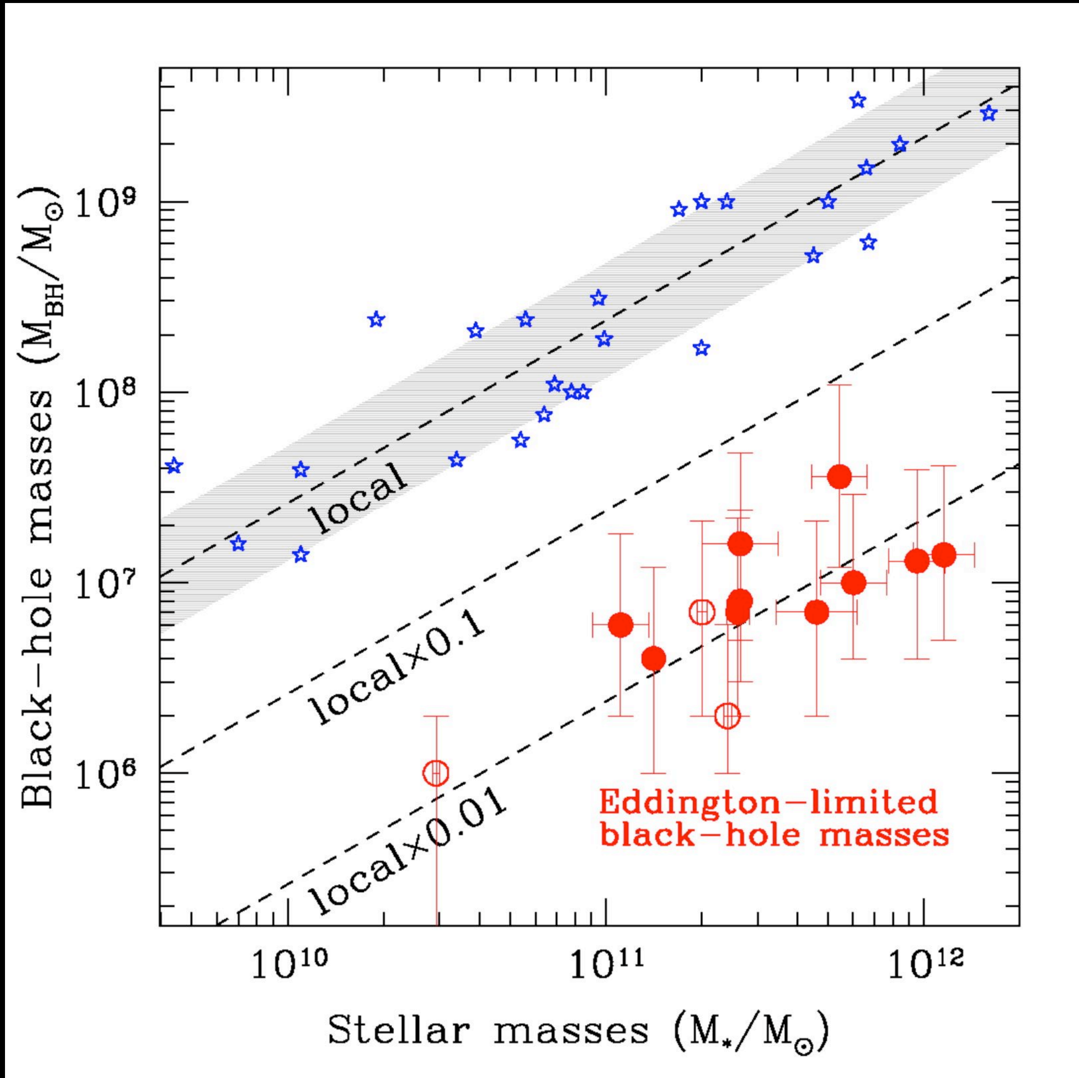


(SST ULIRGs)

- Dependence on infrared luminosity
- AGN dominance: ~40% (ULIRGs) → ~85% (HLIRGs)

Small number of objects…

SMGs: $M_{BH} - M_*$ relation



BH masses: CXO
Stellar masses: SST / IRAC

$$\frac{M_{BH}(z\sim2)}{M_{stellar}} \sim \frac{1}{50}\frac{M_{BH}(z\sim0)}{M_{stellar}}$$

- $L < L_{Edd}$???

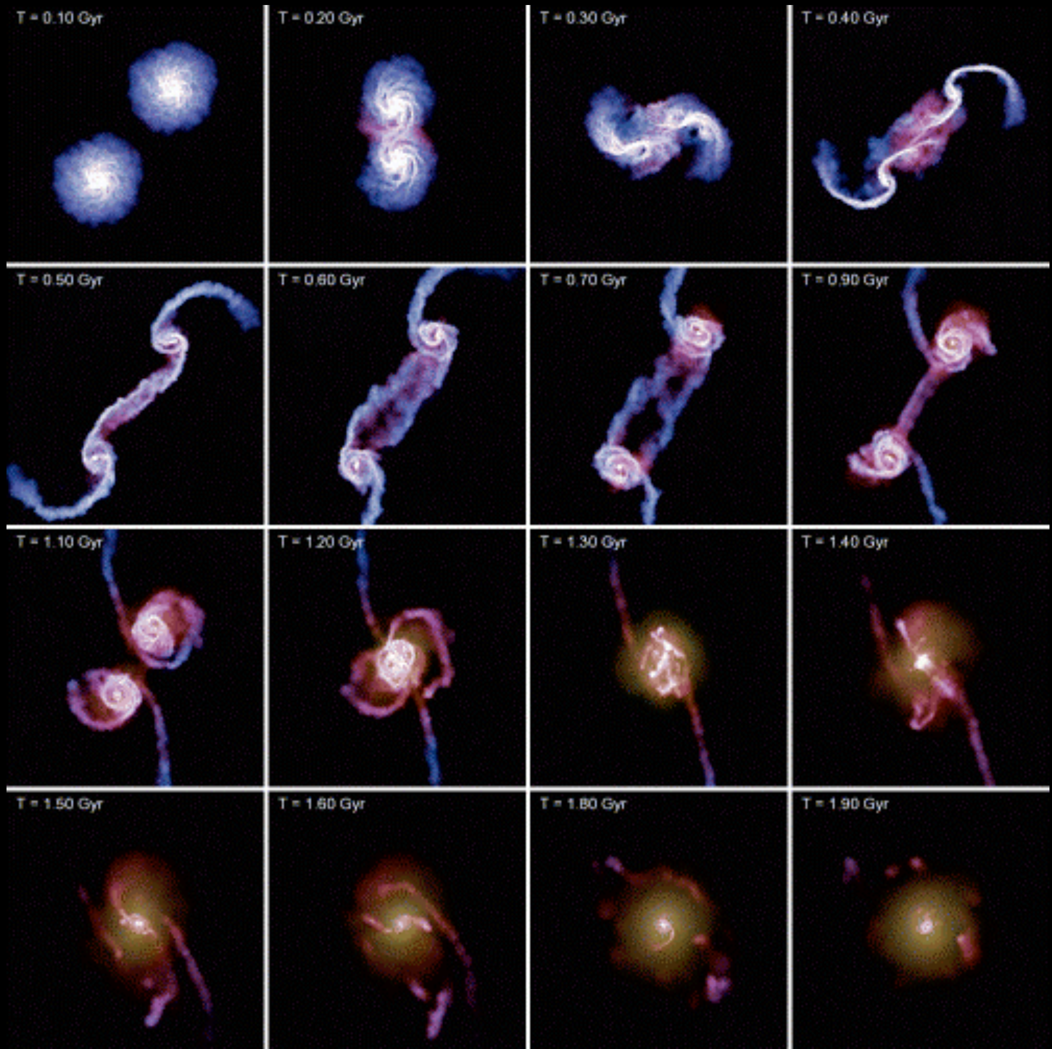
- Compton-thick AGN ???

New Results on SMGs w/ BLRs

$$\frac{M_{BH}(z\sim2)}{M_{stellar}} \sim \frac{1}{10}\frac{M_{BH}(z\sim0)}{M_{stellar}}$$

Selection effects…

ULIRG – Spheroid/QSO in formation
(low-to-moderate z)



- ***Forming spheroids***
- ***Black hole growth***
- ***Galactic winds***

Gas

(Springel, di Matteo, & Hernquist 2005)

ULIRG – Spheroid/QSO in formation (high-z)

Gas *(Li et al. 2006)* Stars